

Rotation Crop Evaluation for Management of the Soybean Cyst Nematode in Minnesota

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ABSTRACT

Crop rotation is an effective tactic for soybean cyst nematode (SCN) management. In the North Central region of the USA, corn is almost exclusively used as a nonhost rotation crop with soybean. This study was conducted to determine the effectiveness of crops common to or having potential use in the North Central region as rotation crops for managing SCN. Sixteen potential rotation crops and SCN-resistant and susceptible soybeans were grown along with six fallow controls in three commercial field sites near Waseca, Lamberton, and Morris, MN, in 2001, and SCN-susceptible soybean was grown on all plots in 2002. Nematode populations at planting, midseason, and harvest were measured both years; soybean yield was measured in 2002. There was large variability in SCN populations and soybean yields at the three sites. Nevertheless, significant treatment effects were detected at all sites. While all of the rotation crops lowered SCN populations compared with SCN-susceptible soybean, there were only subtle differences among the individual rotation crops and among different groups of the crops. Leguminous nonhosts or poor hosts were best in reducing SCN population density. Corn, the most common rotation crop in Minnesota, was among the least effective in reducing nematode populations. There was an undetectable yield benefit from SCN management, although differences in yield were observed among the rotation crop treatments—probably due to agronomic factors. The data suggest that a single year of rotation of soybean with any of these crops before planting a susceptible soybean may not be sufficient in managing SCN.

THE soybean cyst nematode, *Heterodera glycines* Ichinohe, was first detected in Minnesota in 1978 (MacDonald et al., 1980). Since then, the SCN has been detected in most (55) counties in southern and central Minnesota where soybean [*Glycine max* (L.) Merr.] is grown. The nematode has become a major yield-limiting factor in the state (Chen et al., 2001a). Management of the nematode has been dependent on planting resistant cultivars and the use of crop rotations (Schmitt, 1991; Niblack and Chen, 2004).

A number of studies have reported on the effect of rotation crops on SCN populations and soybean yields

(Ross, 1962; Weaver et al., 1988; Edwards et al., 1988; Rodriguez-Kabana et al., 1991; Weaver et al., 1993; Koenning et al., 1993; Hershman and Bachi, 1995; Koenning et al., 1995; Howard et al., 1998; Long and Todd, 2001; Chen et al., 2001c; Noel and Wax, 2003). In these studies, however, only one or a few nonhost (mainly corn [*Zea mays* L.], wheat [*Triticum aestivum* L.], and sorghum [*Sorghum bicolor* (L.) Moench] or poor-host crops were compared with soybean. In general, SCN population densities following a nonhost or poor host were lower than following soybean. The effectiveness of crop rotation depends on the host status of crop species, the number of years of rotation crops, and geographical location. For example, in North Carolina, 1 to 2 yr of a nonhost in a rotation was generally sufficient to lower SCN population density to below damaging levels (Schmitt, 1991; Koenning et al., 1993). In contrast, 5 yr of nonhost and SCN-resistant soybean may be needed in Minnesota to reduce the SCN population density to a low level where a susceptible cultivar can be grown without significant yield loss (Chen et al., 2001c). Although most nonhost species tested in fields had similar influence on mortality (Niblack and Chen, 2004), variations in effects of crop species on the SCN have been reported from greenhouse (Riga et al., 2001) and field (Rodriguez-Kabana et al., 1991) studies. Annual ryegrass (*Lolium multiflorum* Lam.) was more effective than other nonhosts in reducing infectivity of soybean by SCN (Riga et al., 2001). In a field study, corn appeared to be more effective than sorghum in lowering SCN second-stage juvenile population densities at the end of the following soybean season (Rodriguez-Kabana et al., 1991).

The mechanisms through which rotation crops affect SCN populations are not fully understood. Some non-host and poor-host crops may be effective in lowering nematode population densities by producing root exudates or decomposition products toxic to the nematodes. For example, *Brassica* spp., such as cabbage, rapeseed, and mustard, produce chemicals as they decompose that are toxic to nematodes (Ellenby, 1945; Mojtahedi et al., 1993; Donkin et al., 1995). Also, phenolic acids from some cereal crops such as wheat can be involved in reducing SCN population densities (Hershman and Bachi, 1995; Blum, 1996). A poor-host crop such as pea (*Pisum sativum* L.) may stimulate SCN to hatch, but the nematodes may not be able to reproduce well (Sortland and MacDonald, 1987; Schmitt and Riggs, 1991). Therefore, growing a poor-host crop may reduce SCN population

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Abbreviations: PCF, population change factor; Pi01, Pm01, Pf01, Pi02, Pm02, and Pf02, soybean cyst nematode egg population density (eggs per 100 cm³) at planting, midseason, and harvest in 2001, and at planting, midseason, and harvest in 2002, respectively; SCN, soybean cyst nematode.

density (Chen et al., 2001b). Riga et al. (2001) looked at the potential of plant residues and plant root exudates to protect soybean from SCN and found that incorporation of residues from a number of plant species into the soil reduced nematode population densities compared with incorporation of soybean residues alone.

In southern Minnesota, corn is almost exclusively used as the nonhost crop in rotation with soybean. The SCN egg densities were reduced 20 to 80% during a year when corn was grown (Chen et al., 2001c). The overwinter survival rate of SCN is high in the northern regions of the USA (Riggs et al., 2001), however, and consequently more frequent use of nonhost crops is necessary compared with the southern USA. Increasing the number of years of corn in a rotation sequence to reduce SCN is not advisable due to the yield penalty associated with corn following corn (Crookston et al., 1991; Porter et al., 1997; Porter et al., 2001; Chen et al., 2001c). Therefore, a need exists to find alternative, economically acceptable nonhost crops for use in rotation with soybean for long-term effective management of the nematode. Field crops commonly produced in Minnesota that were classified as nonhost or poor-host crops for the SCN include alfalfa (*Medicago sativa* L.), barley (*Hordeum vulgare* L.), canola (*Brassica napus* L.), corn, sorghum, oat (*Avena sativa* L.), pea, potato (*Solanum tuberosum* L.), rye (*Secale cereale* L.), red clover (*Trifolium pretense* L.), sugarbeet (*Beta vulgaris* L.), sunflower (*Helianthus annuus* L.), and wheat (Riggs, 1992; Riggs and Hamblen, 1962, 1966). Our objective was to evaluate crops common to Minnesota for their potential use as rotation crops with soybean in the management of the SCN.

MATERIALS AND METHODS

Field Sites

This research was conducted on three commercial farms in south-central (Waseca), southwest (Lamberton), and west-central (Morris) Minnesota in 2001 and 2002. At each location, a field was selected and planted with SCN-susceptible soybean in 2000. In the spring of 2001, the Waseca, Lamberton, and Morris fields had natural SCN infestations of 4120, 20700, and 26300 SCN eggs per 100 cm³ of soil, respectively (Tables 1, 2, and 3). The soil at the Waseca site is Nicolett clay loam (fine-loamy, mixed, superactive, mesic Aquic Hapludoll) and Canisteo clay loam (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquoll). The soil at the Lamberton site is a Canisteo clay loam, and the soil at the Morris site is a Hamerly clay loam (fine-loamy, mixed, superactive, frigid Aeric Calciaquoll).

Experimental Design

The experiment consisted of 24 treatments in a completely randomized block design with six replicates. The 24 treatments were combinations of crops and fallow with appropriate herbicides (Table 1). The experimental unit was a 4.57 by 3.05 m plot. The 16 crops commonly produced in Minnesota or having potential use in the state were selected as rotation crops for this study: barley, flax (*Linum usitatissimum* L.), oat, sorghum, wheat, buckwheat (*Fagopyrum sagittatum* Gilib), canola, corn, rye, sugarbeet, potato, sunflower, alfalfa, hairy

vetch (*Vicia villosa* Roth), red clover, and pea. The controls included an SCN-resistant soybean cultivar (Pioneer 9234), an SCN-susceptible soybean cultivar (Parker), fallow with each herbicide commonly used for these crops (fallow with Buctril [bromoxynil (3,5-dibromo-4-hydroxybenzonitrile)], fallow with Liberty [glufosinate (2-amino-4-(hydroxymethylphosphinyl)butanoic acid)], fallow with Prowl [pendimethalin (N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine)], and fallow with Pursuit [imazethapyr (2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid)]), fallow with hand weeding, and fallow without weed control.

Plot Establishment and Maintenance

The rotation crops were planted in mid-May 2001 except for rye, which was planted in the fall following corn harvest. Barley, flax, oat, alfalfa, hairy vetch, red clover, rye, and pea were all planted with 25-cm row spacing, while sorghum, corn, sugarbeet, potato, sunflower, and soybean were planted with 76-cm row spacing. The pre-emergence herbicide Prowl (pendimethalin, 1.388 kg a.i. ha⁻¹ [N-(1-ethylpropyl)-2,6-dinitro-3,4-xylidine]) was applied before planting, and Buctril (0.280 kg a.i. ha⁻¹), Liberty (0.410 kg a.i. ha⁻¹), or Pursuit (0.070 kg a.i. ha⁻¹) postemergence herbicides were applied 5 wk after planting to the appropriate crops. The corn (Pioneer 37H26 LL), sugarbeet (2012 LL), and canola (InVigor 2573) cultivars were Liberty tolerant. No postemergence herbicide was used on potato and sunflower plots. The corn, sunflower, sugarbeet, potato, and soybean crops were harvested. Residue from all crops was mowed in October and incorporated into the soil with a rototiller at the Waseca and Lamberton sites and with a moldboard plow at the Morris site. In early May 2002, rye in the corn-rye treatment was rototilled to incorporate the residue, and all treatments were field cultivated before planting. In mid-May, the SCN-susceptible soybean 'Pioneer 92B36' was planted at Waseca and Lamberton and 'Asgrow 1602' was planted at Morris in all plots at 76-cm row spacing. Both cultivars were resistant to Roundup (glyphosate [N-(phosphonomethyl) glycine]), so Roundup at 0.683 kg a.i. ha⁻¹ was applied in mid-July to control weeds.

Nematode Population and Yield Measurements

Nematode egg densities were determined at planting (Pi), at midseason (Pm, 2 mo after planting), and at harvest (Pf) both years. In 2001, a composite soil sample consisting of 20 cores was taken with a 2.5-cm-diam. soil probe to a 20-cm depth across the central area of approximately 3.5 by 1.5 m of each plot. In 2002, the soil samples were taken from near the soybean root zone of the two central rows of each plot. The soil samples were stored in a cool room (4°C) before being processed. Each soil sample was thoroughly mixed and cysts were extracted from a subsample of 100 cm³ of soil with a semi-automatic elutriator (Byrd et al., 1976) and separated from soil particles and debris with centrifugation in a 63% (w/v) sucrose solution. Eggs were released from the cysts mechanically (Faghihi and Ferris, 2000) and collected in a 50-mL tube. The number of eggs was counted in 0.5 to 2.0 mL of the egg suspension, depending on the number of eggs, and the total number of eggs in 100 cm³ of soil was derived. The nematode population density was expressed as number of eggs per 100 cm³ of soil. To determine nematode population change during the crop season, population change factors (PCF) were computed. The PCF at midseason 2001, at harvest 2001, and at planting 2002 were determined by dividing the egg densities from Pm01 (at midseason in 2001), Pf01 (at harvest in 2001),

Table 1. Population density of the soybean cyst nematode *Heterodera glycines* at planting, midseason, and harvest in 2001 (Pi01, Pm01, and Pf01, respectively) and 2002 (Pi02, Pm02, and Pf02, respectively) in response to rotation crops in Minnesota–Waseca site.†

Crop in 2001	Herbicide in 2001	2001			2002		
		Pi01	Pm01	Pf01	Pi02	Pm02	Pf02
eggs per 100 cm³ soil							
Barley	Buctril	3750	5079	3267ab‡	1513b	3489ab	13967
Flax	Buctril	4625	3402	2717abc	1777ab	3446ab	10667
Oat	Buctril	4146	3896	2313bc	1717b	3755ab	10242
Sorghum	Buctril	5054	4817	2695bc	2715ab	5788a	8406
Wheat	Buctril	3800	3367	2373bc	1583b	4800a	10742
Buckwheat	Buctril	1817	3954	2375bc	2025ab	2375ab	10033
Canola	Liberty	3292	3433	2283bc	2025ab	2504ab	10367
Corn	Liberty	4063	4000	2625abc	1725ab	2029ab	9083
Corn-rye	Liberty	5967	4971	3717abc	3213ab	2017ab	12192
Sugarbeet	Liberty	4921	5021	4313abc	1858b	4943ab	11333
Potato	Prowl	4596	3075	2194bc	1360b	3825ab	14092
Sunflower	Prowl	3463	2690	2183bc	1415b	3213ab	11408
Alfalfa	Pursuit	4181	3238	2356bc	1875b	2100ab	8575
Hairy vetch	Pursuit	3854	2725	3896ab	2988ab	1163b	6942
Red clover	Pursuit	2754	3004	1710c	1700b	2229ab	12125
Pea	Pursuit	2969	2842	2138bc	1431b	4092ab	9092
Soybean (S)§	Pursuit	2969	3488	8388a	5988a	3542ab	11000
Soybean (R)§	Pursuit	4700	3663	2213bc	867b	2914ab	10858
Fallow	Buctril	5504	4671	2090bc	1731b	3220ab	11467
Fallow	Liberty	4108	2850	2248bc	1754ab	4497a	11292
Fallow	Prowl	5171	4892	3021abc	3154ab	3746ab	14483
Fallow	Pursuit	5800	3388	2358bc	1500b	2850ab	11650
Fallow	Hand weeding	4356	4129	2658abc	1469b	4833a	12917
Fallow	No weeding	3096	3813	1379bc	1767ab	2033ab	7500
Average by group¶							
Monocots (1)		4463	4355	2831	2077	3646	10772
Nonleguminous dicots (2)		3785	3596	2677	1743	3384	11317
Leguminous nonhost and poor-host dicots (3)		3301	3028	2068	1669	2807	9931
Fallow with herbicide (4)		5146	3950	2429	2035	3578	12223
Contrast							
1 vs. 2		NS#	*	NS	NS	NS	NS
1 vs. 3		*	**	*	NS	NS	NS
1 vs. 4		NS	NS	NS	NS	NS	*
2 vs. 3		NS	NS	*	NS	NS	NS
2 vs. 4		*	NS	NS	NS	NS	NS
3 vs. 4		**	NS	NS	NS	NS	*

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

† SCN-susceptible soybean was grown in all plots in 2002. Data were transformed with $\log_{10}(x + 1)$ before being subjected to analysis of variance (ANOVA).

‡ The values are means of six replicates.

§ Within columns, values followed by the same letter or no letter are not significantly different according to Tukey's Studentized Range (HSD) Test at $P \geq 0.05$.

¶ S = SCN susceptible; R = SCN resistant.

|| Monocot crops include barley, oat, sorghum, wheat, corn, and corn–rye; nonleguminous dicots include flax, buckwheat, canola, sugarbeet, potato, and sunflower; leguminous nonhost and poor-host dicots include alfalfa, red clover, and pea.

NS = not significant at $P \geq 0.05$.

and Pi02 (at planting in 2002), respectively, by the egg densities from Pi01 (at planting in 2001). The PCF at harvest of soybean in 2002 was determined by dividing the egg densities from Pf02 (at harvest in 2002) by the egg densities from Pi02.

Soybean yields were measured in 2002 from a 4.57-m length of the two central rows with a small plot combine. The soybean yield was standardized at 130 g kg⁻¹ moisture.

Data Analysis

The data were initially analyzed using SAS repeated measures ANOVA with whole plots at the three locations, blocks within locations, and treatments within blocks. The repeated measure was conducted on $\log_{10}(x + 1)$ -transformed nematode population densities and PCFs. There was no transformation for yield data. All sampling date effects, date \times location, date \times treatment, and date \times location \times treatment interactions were highly significant ($P < 0.0001$), so we continued the analysis of each date and location separately, treating the study

as a randomized complete block design. At Lamberton, severe Fe-deficiency chlorosis affected late season growth across two blocks and consequently these two blocks were removed from the data set (Pm02, Pf02, PCF at harvest, and soybean yield in 2002) before analysis. Means of individual treatments were compared using Tukey's Studentized Range (HSD) test at $\alpha = 0.05$. To determine differences among groups of crop treatments, the data were averaged in four groups: (i) monocots (barley, oat, sorghum, wheat, corn, and corn–rye); (ii) nonleguminous dicots (flax, buckwheat, canola, sugarbeet, potato, and sunflower); (iii) leguminous nonhosts or poor hosts (alfalfa, red clover, and pea); and (iv) fallows with herbicide treatments, and contrasts were performed. Soybean and hairy vetch were hosts of the nematode and were excluded from any of the groups. Regressions of PCF at 2002 harvest against Pi02 with the linear model $\ln(\text{PCF}) = \ln(a) + b \ln(\text{Pi02})$ derived from the equation $\text{PCF} = a(\text{Pi02})^b$ (Ferris, 1985) were performed to determine relationships between PCF during the soybean-growing season and the initial nematode density, and

Table 2. Population density of the soybean cyst nematode *Heterodera glycines* at planting, midseason, and harvest in 2001 (Pi01, Pm01, and Pf01, respectively) and 2002 (Pi02, Pm02, and Pf02, respectively) in response to rotation crops in Minnesota-Lamberton site.†

		2001			2002		
Crop in 2001	Herbicide in 2001	Pi01	Pm01	Pf01	Pi02	Pm02	Pf02
eggs per 100 cm ³ of soil							
Barley	Buctril	14 500	18 750ab‡	16 533	11 150	15 250	16 650ab
Flax	Buctril	11 992	21 533a	18 467	12 417	19 050	15 713ab
Oat	Buctril	10 717	14 933ab	14 033	9 500	18 550	14 875ab
Sorghum	Buctril	15 050	19 683ab	18 433	15 733	14 375	10 475b
Wheat	Buctril	15 283	23 192ab	18 150	13 842	21 275	23 900a
Buckwheat	Buctril	11 733	19 700ab	16 533	14 383	12 575	14 438ab
Canola	Liberty	15 283	14 875ab	15 733	11 833	19 250	8 575b
Corn	Liberty	14 771	20 400ab	12 833	11 654	18 375	10 950b
Corn-rye	Liberty	14 650	20 817ab	15 500	13 233	15 025	9 316b
Sugarbeet	Liberty	12 383	19 767ab	16 083	13 900	13 750	9 325b
Potato	Prowl	13 750	20 800a	13 833	11 967	12 825	17 250ab
Sunflower	Prowl	10 858	18 400ab	15 125	11 021	15 625	14 100ab
Alfalfa	Pursuit	14 100	18 750ab	15 442	13 083	19 900	11 691ab
Hairy vetch	Pursuit	10 100	15 583ab	13 917	11 858	15 250	15 663ab
Red clover	Pursuit	12 717	20 067ab	11 708	14 208	15 050	13 938ab
Pea	Pursuit	13 733	14 550ab	13 433	10 800	13 738	8 500b
Soybean (S)§	Pursuit	12 750	21 850a	23 517	17 250	16 025	13 400ab
Soybean (R)§	Pursuit	17 550	10 542b	12 317	11 425	16 375	11 075ab
Fallow	Buctril	9 433	19 017ab	13 500	9 983	13 575	9 800b
Fallow	Liberty	12 183	19 633ab	12 450	13 446	19 775	13 316ab
Fallow	Prowl	14 933	18 883ab	17 817	15 867	13 200	18 138ab
Fallow	Pursuit	19 133	21 033ab	18 258	12 492	19 850	9 825b
Fallow	Hand weeding	12 625	23 183ab	15 200	14 183	15 150	10 400b
Fallow	No weeding	13 783	16 083ab	12 283	11 850	14 950	13 988ab
Average by group¶							
Monocots (1)		14 162	19 629	15 914	12 519	17 142	14 361
Nonleguminous dicots (2)		12 667	19 179	15 962	12 587	15 513	13 234
Leguminous nonhost and poor-host dicots (3)		13 517	17 789	13 528	12 697	16 229	11 376
Fallow with herbicide (4)		13 921	19 642	15 506	12 947	16 600	12 770
Contrast							
1 vs. 2		NS#	NS	NS	NS	NS	NS
1 vs. 3		NS	NS	NS	NS	NS	NS
1 vs. 4		NS	NS	NS	NS	NS	NS
2 vs. 3		NS	NS	NS	NS	NS	NS
2 vs. 4		NS	NS	NS	NS	NS	NS
3 vs. 4		NS	NS	NS	NS	NS	NS

† SCN-susceptible soybean was grown in all plots in 2002. Data were transformed with $\log_{10}(x + 1)$ before being subjected to analysis of variance (ANOVA). The values are means of six replicates.

‡ Within columns, values followed by the same letter or no letter are not significantly different according to Tukey's Studentized Range (HSD) Test at $P \geq 0.05$.

§ S = SCN susceptible; R = SCN resistant.

¶ Monocot crops include barley, oat, sorghum, wheat, corn, and corn-rye; nonleguminous dicots include flax, buckwheat, canola, sugarbeet, potato, and sunflower; leguminous nonhost and poor-host dicots include alfalfa, red clover, and pea.

NS = not significant at $P \geq 0.05$.

to determine an equilibrium density on susceptible soybean. In this analysis, because there was no significant interaction between Pi02 and location, the data of the three sites were pooled together.

RESULTS

Soybean Cyst Nematode Population Densities

The SCN population densities at Waseca, Lamberton, and Morris are presented in Tables 1, 2, and 3, respectively. At Waseca, Pf01 and Pi02 in the rotation crop treatments except for flax, corn, corn-rye, and hairy vetch were significantly lower than that following susceptible soybean (Table 1). The Pm02 in the hairy vetch treatment was lower than in the sorghum and wheat treatments. No differences were observed among the fallows with different weed-control treatments. Contrast analysis showed that Pm01 and Pf01 were lower in leguminous nonhosts and poor hosts than monocots, and

Pf01 was also lower in leguminous nonhosts and poor hosts than nonleguminous dicots. Nonleguminous dicots resulted in lower Pm01 than monocots (Table 1); however, the Pi01 were lower in plots of nonleguminous dicots and the plots of leguminous nonhosts and poor hosts than the monocots and fallow plots, suggesting that the difference in Pm01 and Pf01 could be due to experimental error. At 2002 harvest, the average egg density with fallow with herbicides was higher than with monocots and leguminous dicots.

At Lamberton, significant differences for SCN population densities were detected at midseason 2001 and harvest 2002 (Table 2). The Pm01 in plots with resistant soybean was lower than in plots with susceptible soybean, potato, and flax. The Pf02 was higher in the wheat treatment than in the canola, corn, corn-rye, sugarbeet, and pea treatments. No significant differences were detected among other individual crop treatments or between the groups of treatments (Table 2).

Table 3. Population density of the soybean cyst nematode *Heterodera glycines* at planting, midseason, and harvest in 2001 (Pi01, Pm01, and Pf01, respectively) and 2002 (Pi02, Pm02, and Pf02, respectively) in response to rotation crops in Minnesota–Morris site.†

		2001			2002		
Crop in 2001	Herbicide in 2001	Pi01	Pm01	Pf01	Pi02	Pm02	Pf02
— eggs 100 cm ⁻³ soil —							
Barley	Buctril	19 567	20 383	22 500bc‡	18 300abcd	14 017	12 117abcd
Flax	Buctril	29 033	23 683	28 717abc	21 300abc	10 983	9 083cd
Oat	Buctril	24 000	28 383	25 750abc	20 517abc	10 250	12 067abcd
Sorghum	Buctril	30 642	26 683	27 283abc	16 967abcd	10 783	14 600abcd
Wheat	Buctril	32 833	26 817	32 967abc	26 733ab	12 983	13 283abcd
Buckwheat	Buctril	21 350	26 533	25 475abc	17 600abcd	11 600	8 383cd
Canola	Liberty	26 250	21 233	24 600abc	17 000abcd	11 100	9 333cd
Corn	Liberty	25 167	27 967	19 733bc	17 467abcd	12 367	17 867ab
Corn-rye	Liberty	27 983	28 750	29 383abc	20 500abc	14 417	10 900abcd
Sugarbeet	Liberty	33 400	21 150	26 417abc	20 967abc	10 367	11 217abcd
Potato	Prowl	29 850	27 467	24 983abc	17 950abcd	10 283	13 167abcd
Sunflower	Prowl	20 000	25 883	26 783abc	16 550abcd	13 633	16 317abc
Alfalfa	Pursuit	27 550	18 683	24 633abc	18 317abcd	10 583	20 083a
Hairy vetch	Pursuit	27 100	20 500	25 817abc	18 733abcd	12 183	14 750abcd
Red clover	Pursuit	27 033	22 667	22 500bc	19 567abc	9 483	19 350ab
Pea	Pursuit	28 450	21 050	23 300abc	12 517cd	8 700	11 617abcd
Soybean (S)§	Pursuit	20 033	20 117	42 933a	30 217a	14 167	11 583abcd
Soybean (R)§	Pursuit	31 867	20 500	18 642c	10 950d	9 380	13 383abcd
Fallow	Buctril	18 117	21 100	24 017abc	15 733bcd	8 850	7 517d
Fallow	Liberty	24 955	24 433	24 500abc	16 850abcd	9 183	12 350abcd
Fallow	Prowl	32 267	25 333	25 033abc	18 383abcd	13 467	12 083abcd
Fallow	Pursuit	25 515	20 683	22 050bc	16 833abcd	10 567	9 167cd
Fallow	hand weeding	26 517	28 733	27 967abc	20 200abc	13 417	9 767bcd
Fallow	no weeding	20 783	22 333	34 883ab	20 067abc	12 080	19 200ab
Average by group¶							
Monocots (1)		26 699	26 497	26 269	20 081	12 470	13 472
Nonleguminous dicots (2)		26 647	24 325	26 163	18 561	11 328	11 250
Leguminous nonhost and poor-host dicots (3)		27 678	20 800	23 478	16 800	9 589	17 017
Fallow with herbicide (4)		25 214	22 887	23 900	16 950	10 517	10 279
Contrast							
1 vs. 2		NS#	NS	NS	NS	NS	**
1 vs. 3		NS	*	NS	**	*	*
2 vs. 3		NS	NS	NS	NS	NS	***
3 vs. 4		NS	NS	NS	NS	NS	***
2 vs. 4		NS	NS	NS	NS	NS	NS
1 vs. 4		NS	*	NS	*	NS	**

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† SCN-susceptible soybean was grown in all plots in 2002. Data were transformed with $\log_{10}(x + 1)$ before being subjected to analysis of variance (ANOVA). The values are means of six replicates.‡ Within columns, values followed by the same letter or no letter are not significantly different according to Tukey's Studentized Range (HSD) Test at $P \geq 0.05$.

§ S = SCN susceptible; R = SCN resistant.

¶ Monocot crops include barley, oat, sorghum, wheat, corn, and corn-rye; nonleguminous dicots include flax, buckwheat, canola, sugarbeet, potato, and sunflower; leguminous nonhost and poor-host dicots include alfalfa, red clover, and pea.

NS = not significant at $P \geq 0.05$.

At Morris, significant differences between individual treatments were detected at harvest 2001, at planting 2002, and at harvest 2002 (Table 3). Susceptible soybean had a higher Pf01 than resistant soybean, barley, corn, and red clover, and a higher Pi02 than resistant soybean and pea. The Pi02 in the resistant soybean was lower than in flax, oat, wheat, corn-rye, sugarbeet, and red clover. At harvest 2002, the SCN population did not differ from those in susceptible plots, although the alfalfa treatment resulted in higher egg population density than flax, buckwheat, or canola. In fallow plots, the Pf02 was higher in the no-weeding treatment than in treatments with either Buctril or Pursuit. By group, fallow and leguminous nonhosts and poor hosts resulted in lower Pm01 and Pi02 than monocots (Table 3). The treatment with leguminous nonhosts and poor hosts resulted in higher ($P < 0.05$ or 0.001) Pf02 than any

other group of crops or fallow (Table 3). Monocots also resulted in higher ($P < 0.01$) Pf02 than nonleguminous dicots and fallow.

Population Change Factor

At Waseca, the PCF during and after the 2001 rotation crop season of the susceptible soybean treatment was higher than that of other crops, except buckwheat, on at least one of the three sampling occasions (2001 midseason, 2001 harvest, and 2002 at planting; Table 4). The PCF was 2.56 at planting in 2002 following susceptible soybean, indicating a population increase, and the PCF following the other crops except buckwheat was < 1 , indicating a decrease in the egg population density. The resistant soybean resulted in the lowest PCF at planting in 2002 (Table 4). Fallow treatments

Table 4. Population change factor of *Heterodera glycines* in response to rotation crops in Minnesota–Waseca site.†

Crop in 2001	Herbicide in 2001	2001 rotation crops		2002 soybean	
		Midseason	Harvest	Planting	Harvest
Barley	Buctril	1.53ab‡	0.98ab	0.43bc	11.51ab
Flax	Buctril	0.78b	0.87b	0.50bc	6.46abc
Oat	Buctril	0.98ab	0.61b	0.48bc	6.65abc
Sorghum	Buctril	1.02ab	0.69b	0.64abc	3.92bc
Wheat	Buctril	0.87ab	0.56b	0.42bc	12.85ab
Buckwheat	Buctril	2.25a	1.38ab	1.09ab	7.64abc
Canola	Liberty	1.00ab	0.74b	0.65abc	6.65abc
Corn	Liberty	1.33ab	0.95b	0.57bc	5.24abc
Corn-rye	Liberty	0.99ab	0.67b	0.59abc	4.70abc
Sugarbeet	Liberty	1.09ab	0.90b	0.37bc	9.87abc
Potato	Prowl	0.86b	0.63b	0.46bc	20.31a
Sunflower	Prowl	0.82b	0.67b	0.45bc	11.08ab
Alfalfa	Pursuit	0.96ab	0.65b	0.47bc	7.63abc
Hairy vetch	Pursuit	0.72b	1.12ab	0.79abc	2.97bc
Red clover	Pursuit	1.18ab	0.61b	0.67abc	7.88abc
Pea	Pursuit	1.17ab	0.91b	0.60bc	10.92ab
Soybean (S)§	Pursuit	1.39ab	3.58a	2.56a	1.89c
Soybean (R)§	Pursuit	0.98ab	0.55b	0.25c	14.31a
Fallow	Buctril	0.86ab	0.40b	0.31bc	12.42ab
Fallow	Liberty	0.81b	0.61b	0.48bc	8.10abc
Fallow	Prowl	1.02ab	0.60b	0.61bc	6.91abc
Fallow	Pursuit	0.59b	0.42b	0.26bc	9.68ab
Fallow	hand weeding	1.29ab	0.80b	0.38bc	10.33ab
Fallow	no weeding	1.53ab	0.59b	0.78abc	5.16abc
Average by group¶					
Monocots (1)		1.12	0.74	0.52	7.48
Nonleguminous dicots (2)		1.13	0.87	0.59	10.34
Leguminous nonhost and poor-host dicots (3)		1.10	0.72	0.58	8.81
Fallow with herbicide (4)		0.82	0.51	0.42	9.28
Contrast					
1 vs. 2		NS#	NS	NS	NS
1 vs. 3		NS	NS	NS	NS
1 vs. 4		*	NS	NS	NS
2 vs. 3		NS	NS	NS	NS
2 vs. 4		*	*	NS	NS
3 vs. 4		NS	NS	NS	NS

* Significant at the 0.05 probability level.

† Population change factor (PCF) in 2001 midseason, 2001 at harvest, and 2002 at planting = egg density at a sampling occasion/egg density at planting in 2001; PCF at 2002 harvest = egg density at harvest/egg density at planting in 2002. Values are means of six replicates. Data were transformed with $\log_{10}(x + 1)$ before being subjected to ANOVA.‡ Within columns, values followed by the same letter or no letter are not significantly different according to Tukey's Studentized Range (HSD) Test at $P \geq 0.05$.

§ S = SCN susceptible; R = SCN resistant.

¶ Monocot crops include barley, oat, sorghum, wheat, corn, and corn-rye; nonleguminous dicots include flax, buckwheat, canola, sugarbeet, potato, and sunflower; leguminous nonhost and poor-host dicots include alfalfa, red clover, and pea.

NS = not significant at $P \geq 0.05$.

resulted in lower PCF than monocots and nonleguminous dicots (Table 4). When susceptible soybean was grown in 2002 in all plots, the PCF was mainly influenced by the egg population density at planting (Pi02). Susceptible soybean in 2001 resulted in a lower PCF at harvest in 2002 than barley, wheat, potato, sunflower, pea, and resistant soybean (Table 4). The PCF with hairy vetch was also lower than with resistant soybean or potato treatments (Table 4).

At Lamberton, there was no difference in PCF during and after the rotation crop season between treatments in most cases; however, the PCF with resistant soybean was lower than with susceptible soybean, flax, oat, wheat, buckwheat, corn, corn-rye, sugarbeet, potato, sunflower, hairy vetch, or red clover at midseason 2001

(Table 5). By group, the PCF at harvest in 2001 was lower in leguminous nonhosts and poor hosts than in nonleguminous dicots (Table 5). No difference in PCF at harvest in 2002 was observed between individual treatments or between groups of treatments at Lamberton.

At Morris, the PCF was higher in susceptible soybean than in sorghum, canola, corn, corn-rye, sugarbeet, potato, alfalfa, hairy vetch, red clover, pea, and resistant soybean at harvest in 2001 and at planting in 2002. The resistant soybean resulted in a lower PCF than most rotation crops at planting in 2002 (Table 6). The PCF for leguminous nonhosts and poor hosts was lower than for monocots, nonleguminous dicots, or fallow. No differences were observed among groups at harvest in 2001. Susceptible soybean in 2001 resulted in a lower PCF at

Table 5. Population change factor of *Heterodera glycines* in response to rotation crops in Minnesota–Lamberton site.†

Crop in 2001	Herbicide in 2001	2001 rotation crops		2002 soybean	
		Midseason	Harvest	Planting	Harvest
Barley	Buctril	1.27ab‡	1.15	0.82	1.51
Flax	Buctril	1.98a	1.74	1.07	1.32
Oat	Buctril	1.45a	1.26	0.91	1.49
Sorghum	Buctril	1.32ab	1.39	1.26	0.56
Wheat	Buctril	1.45a	1.19	0.98	1.50
Buckwheat	Buctril	1.66a	1.41	1.24	0.94
Canola	Liberty	1.01ab	1.05	0.79	0.75
Corn	Liberty	1.35a	1.17	0.86	0.76
Corn-rye	Liberty	1.56a	1.17	0.95	0.64
Sugarbeet	Liberty	1.60a	1.27	1.13	0.63
Potato	Prowl	1.57a	1.04	0.92	1.55
Sunflower	Prowl	1.87a	1.62	1.07	1.02
Alfalfa	Pursuit	1.40ab	1.18	0.96	0.67
Hairy vetch	Pursuit	1.86a	1.89	1.43	1.10
Red clover	Pursuit	1.74a	0.98	1.14	0.77
Pea	Pursuit	1.11ab	1.02	0.77	0.80
Soybean (S)§	Pursuit	1.96a	1.95	1.44	0.71
Soybean (R)§	Pursuit	0.72b	0.77	0.71	0.99
Fallow	Buctril	2.15a	1.52	1.16	0.88
Fallow	Liberty	1.69a	1.03	1.08	0.91
Fallow	Prowl	1.31ab	1.32	1.19	1.15
Fallow	Pursuit	1.13ab	1.00	0.76	0.71
Fallow	hand weeding	2.00a	1.21	1.19	0.62
Fallow	no weeding	1.16ab	0.90	0.85	1.12
Average by group¶					
Monocots (1)		1.40	1.22	0.96	1.08
Nonleguminous dicots (2)		1.62	1.36	1.04	1.04
Leguminous nonhost and poor-host dicots (3)		1.42	1.06	0.96	0.75
Fallow with herbicide (4)		1.57	1.22	1.05	0.91
Contrast					
1 vs. 2		NS#	NS	NS	NS
1 vs. 3		NS	NS	NS	NS
1 vs. 4		NS	NS	NS	NS
2 vs. 3		NS	*	NS	NS
2 vs. 4		NS	NS	NS	NS
3 vs. 4		NS	NS	NS	NS

* Significant at the 0.05 probability level.

† The population change factor (PCF) in 2001 midseason, 2001 at harvest, and 2002 at planting = egg density at a sampling occasion/egg density at planting in 2001; PCF at 2002 harvest = egg density at harvest/egg density at planting in 2002. The values are means of six replicates. Data were transformed with $\log_{10}(x + 1)$ before being subjected to ANOVA.‡ Within columns, values followed by the same letter or no letter are not significantly different according to Tukey's Studentized Range (HSD) Test at $P \geq 0.05$.

§ S = SCN susceptible; R = SCN resistant.

¶ Monocot crops include barley, oat, sorghum, wheat, corn, and corn-rye; nonleguminous dicots include flax, buckwheat, canola, sugarbeet, potato, and sunflower; leguminous nonhost and poor-host dicots include alfalfa, red clover, and pea.

NS = not significant at $P \geq 0.05$.

Table 6. Population change factor of *Heterodera glycines* in response to rotation crops in Minnesota–Morris site.†

Crop in 2001	Herbicide in 2001	2001 rotation crops		2002 soybean	
		Midseason	Harvest	Planting	Harvest
Barley	Buctril	1.07	1.17abc‡	0.97ab	0.67abcd
Flax	Buctril	0.90	1.09abc	0.77abc	0.45cd
Oats	Buctril	1.40	1.20abc	0.95ab	0.60abcd
Sorghum	Buctril	0.88	0.93bc	0.58bcd	0.87abcd
Wheat	Buctril	0.90	1.10abc	0.93abc	0.56abcd
Buckwheat	Buctril	1.34	1.28abc	0.87abc	0.50bcd
Canola	Liberty	0.86	0.95bc	0.68bcd	0.57abcd
Corn	Liberty	1.24	0.89bc	0.80bc	1.06abc
Corn–rye	Liberty	1.11	1.13abc	0.76bc	0.55abcd
Sugarbeet	Liberty	0.72	0.89bc	0.69bcd	0.59abcd
Potato	Prowl	1.00	0.89bc	0.63bcd	0.80abcd
Sunflower	Prowl	1.27	1.34abc	0.82abc	0.98abc
Alfalfa	Pursuit	0.67	0.89bc	0.66bcd	1.34ab
Hairy vetch	Pursuit	0.83	1.01abc	0.78bc	0.80abcd
Red clover	Pursuit	0.96	0.91bc	0.77bc	1.07abc
Pea	Pursuit	0.73	0.82bc	0.44cd	1.01abcd
Soybean (S)§	Pursuit	1.17	2.43a	1.54a	0.44d
Soybean (R)§	Pursuit	0.71	0.69c	0.36d	1.43a
Fallow	Buctril	1.33	1.42abc	0.98ab	0.48bcd
Fallow	Liberty	1.04	1.00abc	0.73bc	0.82abcd
Fallow	Prowl	0.80	0.80c	0.59bcd	0.67abcd
Fallow	Pursuit	0.89	1.04abc	0.83abc	0.57abcd
Fallow	hand weeding	1.15	1.16abc	0.81abc	0.52bcd
Fallow	no weeding	1.19	1.78ab	1.03ab	1.05abc
Average by group¶					
Monocots (1)		1.10	1.07	0.83	0.72
Nonleguminous dicots (2)		1.02	1.07	0.74	0.65
Leguminous nonhost and poor-host dicots (3)		0.79	0.87	0.62	1.14
Fallow with herbicide (4)		1.02	1.07	0.78	0.64
Contrast					
1 vs. 2		NS#	NS	NS	NS
1 vs. 3		*	NS	**	**
1 vs. 4		NS	NS	NS	NS
2 vs. 3		*	NS	*	***
2 vs. 4		NS	NS	NS	NS
3 vs. 4		*	NS	*	***

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† The population change factor (PCF) in 2001 midseason, 2001 at harvest, and 2002 at planting = egg density at a sampling occasion/egg density at planting in 2001; PCF at 2002 harvest = egg density at harvest/egg density at planting in 2002. The values are means of six replicates. Data were transformed with $\log_{10}(x + 1)$ before being subjected to ANOVA.‡ Within columns, values followed by the same letter or no letter are not significantly different according to Tukey's Studentized Range (HSD) Test at $P \geq 0.05$.

§ S = SCN susceptible; R = SCN resistant.

¶ Monocot crops include barley, oat, sorghum, wheat, corn, and corn-rye; nonleguminous dicots include flax, buckwheat, canola, sugarbeet, potato, and sunflower; leguminous nonhost and poor-host dicots include alfalfa, red clover, and pea.

NS = not significant at $P \geq 0.05$.

harvest 2002 than corn, sunflower, alfalfa, red clover, or resistant soybean (Table 5). The PCF with flax was also lower than the resistant soybean or alfalfa treatments (Table 5). The PCF for leguminous nonhosts and poor hosts was higher than for monocots, nonleguminous dicots, or fallow.

Pooling the data of all three sites together, the PCF following soybean was negatively related with the Pi02 ($R^2 = 0.85$, $P < 0.0001$; Fig. 1). There was no difference in the PCF–Pi02 relationship among the three sites. Based on this model (Fig. 1), the predicted equilibrium population density at the three sites at harvest in 2002 was 11 490 eggs per 100 cm³ of soil. At Waseca, the average Pi02 was 2048 (range 125–9125) eggs per 100 cm³ of

soil, and therefore there was an increase in population density. In contrast, the Pi02 at Lamberton and Morris (Tables 2 and 3) were far above the predicted equilibrium population density, and subsequently the population decreased during the soybean-growing season (PCF generally < 1).

Soybean Yield

The response of soybean yield to the treatments varied between sites (Table 7). Yields were highest at Waseca, but no difference was detected except for the corn–rye treatment, which had a lower yield than most other treatments at this site (Table 7). At Lamberton, the soybean yields following corn or corn–rye were lowest; they were significantly lower than the yield following potato and sunflower treatments. By group, fallow treatments resulted in the highest yield followed by nonleguminous dicots, monocots, and leguminous nonhosts and poor hosts (Table 7). Iron-deficiency chlorosis in the field was a major factor influencing soybean yield, which was negatively correlated with the Fe-deficiency chlorosis rating ($r = -0.74$, $P < 0.0001$). Complete yield loss occurred in 47 out of the 144 plots at this site. At Morris, heavy rainfall in June affected early season plant growth and consequently reduced yields. The hairy vetch and sunflower treatments produced higher yields than the canola, flax, or oat treatments (Table 7). By group, treatments of leguminous nonhosts and poor hosts and monocots resulted in higher ($P < 0.05$ or 0.01) yields than nonleguminous dicots and fallow (Table 7).

DISCUSSION

In this study, we demonstrated that all rotation crops resulted in lower SCN egg population density, PCF, or both than susceptible soybean at least at one sampling occasion. This suggests that these crops can be used in rotation for SCN management in Minnesota. After 1 yr of any of these crops, however, the nematode population densities were still > 1000 eggs per 100 cm³ of soil, which

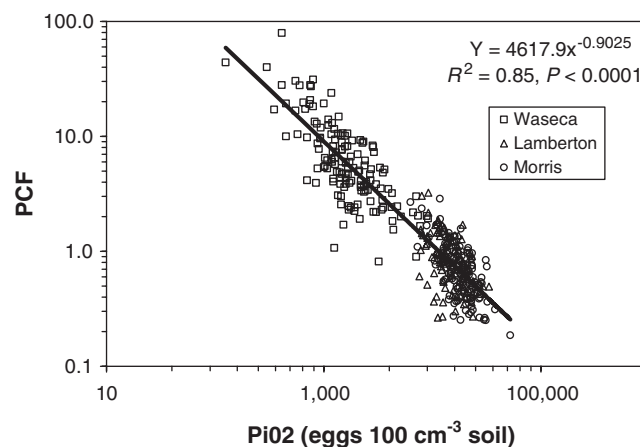


Fig. 1. Relationship between the population change factor (PCF) during the soybean growing season in 2002 and initial egg population density in 2002 (Pi02) at Waseca, Lamberton, and Morris, MN (PCF = egg population density at harvest in 2002/Pi02).

Table 7. Soybean yield response to rotation crops in fields infested with *Heterodera glycines* in Minnesota.[†]

Crop in 2001	Herbicide in 2001	Waseca	Lamberton	Morris
Mg ha ⁻¹				
Barley	Buctril	3.62a‡	2.38abc	0.87bcde
Flax	Buctril	3.23ab	1.82abcd	0.68de
Oat	Buctril	3.52a	2.19abcd	0.74cde
Sorghum	Buctril	3.72a	2.27abcd	1.23abcde
Wheat	Buctril	3.43a	2.32abcd	1.31abcde
Buckwheat	Buctril	3.44a	1.93abcd	0.89bcde
Canola	Liberty	3.44a	2.12abcd	0.61de
Corn	Liberty	3.50a	1.26cd	1.31abcde
Corn-rye	Liberty	2.79b	1.07d	1.38abcd
Sugarbeet	Liberty	3.36ab	2.15abcd	0.90abcde
Potato	Prowl	3.58a	2.56ab	0.90abcde
Sunflower	Prowl	3.32ab	2.57ab	1.67ab
Alfalfa	Pursuit	3.33ab	1.54bcd	1.50abc
Hairy vetch	Pursuit	3.49a	2.17abcd	1.70a
Red clover	Pursuit	3.43a	1.64abcd	1.29abcde
Pea	Pursuit	3.59a	2.37abc	0.98abcde
Soybean (S)§	Pursuit	3.37ab	2.37abc	1.07abcde
Soybean (R)§	Pursuit	3.28ab	2.35abc	1.41abcd
Fallow	Buctril	3.69a	2.41abc	0.85cde
Fallow	Liberty	3.42a	2.48abc	0.83cde
Fallow	Prowl	3.39ab	2.80ab	0.94abcde
Fallow	Pursuit	3.51a	2.83a	0.88bcde
Fallow	hand weeding	3.45a	2.72ab	0.57e
Fallow	no weeding	3.50a	2.49abc	1.30abcde
Average by group¶				
Monocots (1)		3.43	1.92	1.14
Nonleguminous dicots (2)		3.40	2.19	0.94
Leguminous nonhost and poor-host dicots (3)		3.45	1.85	1.26
Fallow with herbicide (4)		3.50	2.63	0.88
Contrast				
1 vs. 2	NS#			
1 vs. 3	NS		*	*
1 vs. 4	NS		***	**
2 vs. 3	NS		*	**
2 vs. 4	NS		**	NS
3 vs. 4	NS		***	**

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

[†] Susceptible soybean 'Pioneer 92B36' and 'Asgrow 1602' were grown at Waseca and Lamberton, and 'Asgrow 1602' was grown at Morris in all plots in 2002. The values are six replicates at Waseca and Morris and three to four replicates at Lamberton.

‡ Within columns, values followed by the same letter or no letter are not significantly different according to Tukey's Studentized Range (HSD) Test at $P \geq 0.05$.

§ S = SCN susceptible; R = SCN resistant.

¶ Monocot crops include barley, oat, sorghum, wheat, corn, and corn-rye; nonleguminous dicots include flax, buckwheat, canola, sugarbeet, potato, and sunflower; leguminous nonhost and poor-host dicots include alfalfa, red clover, and pea.

NS = not significant at $P \geq 0.05$.

can cause significant yield loss to a susceptible soybean (Porter et al., 2001; Chen et al., 2001c). These results were similar to the results of previous studies with corn as the rotation crop, which did not reduce SCN egg population densities to below damaging levels in 1 yr (Porter et al., 2001; Chen et al., 2001c). In general, 5 yr of a corn-resistant soybean rotation were needed for effective SCN management. A similar rotation period may be needed with any of these crops, but further studies are necessary to develop a rotation scheme including any of the alternative crops for SCN management.

Subtle differences in SCN populations among the rotation crops were detected in this study. Leguminous nonhosts and poor hosts appeared to be the best crops

for reducing the SCN population density, while monocots appeared to be the least effective. Similar results have been obtained in greenhouse studies (Vetter et al., 2005). Pea as a trap crop has been shown to reduce SCN population density compared with non-trap-crop treatments in the corn-growing season (Chen et al., 2001b). The leguminous nonhosts and poor hosts may release root exudates to stimulate the SCN to hatch, but the nematodes are not able to develop and reproduce well in these crops (Sortland and MacDonald, 1987; Schmitt and Riggs, 1991), resulting in a population decline. Pea is presently grown in many parts of southern Minnesota and is sometimes double-cropped with soybean. Although it may not be cost effective to use pea as a trap crop interseeded with corn for SCN management (Chen et al., 2001b), it may be a preferred crop for use in rotation with soybean and corn for SCN management. Alfalfa and red clover are perennial crops, and they can be used in rotation with soybean for SCN management where practical. These crops are currently being studied for their potential as cover crops in corn-soybean production systems. Their agronomic and economic potential in the production systems in Minnesota will be further evaluated.

Fallow is rarely used in corn-soybean production in the region. We included fallow with different weed control treatments for the purpose of identifying any herbicide effect on SCN, which might confound the rotation crop effect when different herbicides were used in the different crops. Although the effect of herbicides on SCN population has been reported (Levene et al., 1998), no effect of herbicide on SCN population density was observed in this study except that the Pf02 was higher in the no-weeding treatment than in treatments with either Buctril or Pursuit. Thus, the rotation crop effect on SCN was unlikely to be due to herbicide treatment.

Yield response to the rotation crop was also limited. Soybean yield was not (at Lamberton and Morris) or weakly ($r = -0.19$, $P = 0.02$ at Waseca) correlated with SCN population density (data not shown), suggesting that there was little yield benefit from SCN management with the rotation crop for 1 yr. The response of yield to crop rotation may vary depending on environmental conditions. In a previous study, a 1-yr corn rotation resulted in higher yields than monoculture of soybean in SCN-infested fields at Waseca, but not at Lamberton (Chen et al., 2001c). The difference in yield among some crop treatments in this study was probably due in part to agronomic factors (Porter et al., 1997). At Waseca, the lower soybean yield in the corn-rye treatment was probably due to poor germination of the soybean in this treatment due to the rye residue effect. There were greater differences in soybean yields among crop treatments in Lamberton and Morris, but the trends appear to be opposite between the two sites. At Lamberton, yields following nonleguminous crops and fallow were higher than leguminous nonhosts and poor hosts or monocots; at Morris, the leguminous nonhosts and poor hosts and monocots resulted in higher yields than nonleguminous crops or fallow. The reason for the difference between the two sites is unclear. At Lamberton,

however, these treatments may have affected the development of Fe-deficiency chlorosis; treatments with monocots apparently increased Fe-deficiency chlorosis compared with nonleguminous dicots, especially sugarbeet and canola (data not shown). Subsequently, the soybean yield following monocots was lower than following nonleguminous dicots.

Hairy vetch, a leguminous crop, supported the development of SCN females on the roots in the field and was probably a moderate host of SCN. This is probably why the PCF for hairy vetch was relatively high across the three sites. High PCF was also observed for buckwheat, but the reason is unclear.

Theoretically, the nematode population increases if $PCF > 1$. In this study, however, PCF was >1 for a number of the rotation crops at some sampling occasions, especially at the Lamberton site. This doesn't mean that the nematode population increased in these crops. The higher PCF than what we expected was due to experimental error in soil sampling and sample processing. At the Lamberton site, the average Pi01 was lower than Pm01 and Pf01. The reason for this is unclear.

In the 2002 soybean growing season, predicted equilibrium population density was similar among the three sites. Nematode equilibrium population density is a function of the size of the food source and the efficiency of a nematode population using that food source in producing offspring. Both the size of the food source and the efficiency of use are affected by many factors including cultivar and environment (Seinhorst, 1967; Li and Chen, 2005). The predicted equilibrium population density was the sum of the effects of factors that may have affected food source and the SCN's efficiency in using the food source at the three sites. These factors can be different among sites although the sum of the effects was similar. The equilibrium population density can also be different among years at the same site. The population densities at harvest in 2002 were lower than the population at planting in 2001 at Lamberton and Morris, suggesting that the environmental conditions were more favorable for SCN population development in the 2000 soybean growing season than the 2002 season.

In conclusion, there was large variability in the SCN populations and soybean yields at the three sites. Nevertheless, significant treatment effects were detected at all sites. While all of the rotation crops lowered SCN population compared with SCN-susceptible soybean, there were subtle differences among the individual rotation crops and among different groups of crops. Leguminous nonhosts and poor hosts were probably the best crops in reducing SCN population density. Corn, the most common rotation crop in Minnesota, was in the group that was the least effective in reducing the nematode population.

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